Time-domain Wake-rotor Interaction

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Introduction

Vertical take-off and landing (VTOL) vehicles are an emerging capability in urban mobility. Since communities are already sensitive to the noise generated by commercial airliners and helicopters, a major hurdle for urban VTOL is its acceptance by communities due to its noise impact. In order to design sufficiently quiet VTOL aircraft, an understanding of its source mechanisms is required.

A predominant design for urban VTOL is distributed electric propulsion. This allows some rotors to be located near the front of the vehicle while other rotors near the rear of the vehicle. The wake of a rotor located forward on the vehicle may convect downstream into another rotor. This causes a time-dependent non-uniform inflow for the downstream rotor.

Calculating the radiated noise from a rotor generally requires the inflow turbulence statistics, whether modeled or measured. Complicated inflows like the one described with distributed electric propulsion are challenging to model. Current noise models expect uniform turbulent inflow and typically are done in the frequency domain or only deal with the mean part of the time/spatially varying inflow. Neither of these include time varying turbulent inflow.

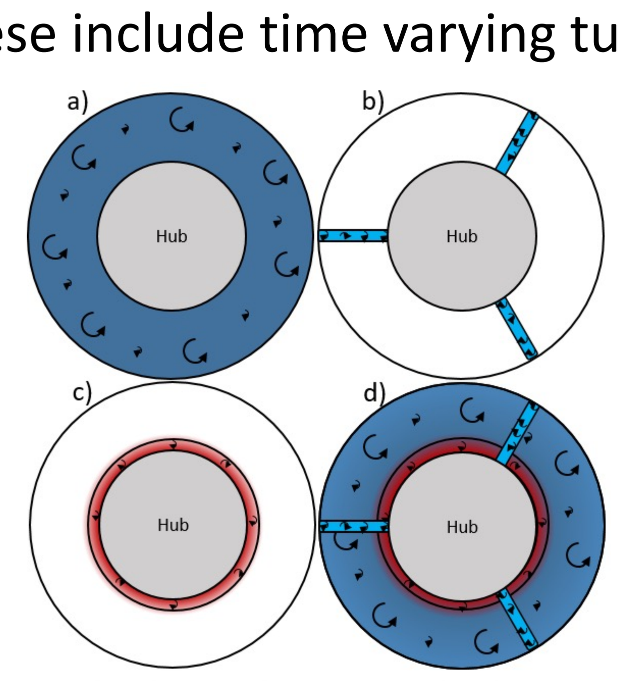

Figure 1: A pictogram of a) uniform turbulent inflow, b) non-uniform inflow due to wake turbulence, c) non-uniform inflow due to boundary layer turbulence, d) a combination of a) through c)

However, in 1983, Ishimaru[1] derived a noise model for inflows with turbulent wakes. As part of the work, he expressed the lift cross-correlation for an inflow with turbulent wakes in terms of an analytical turbulence model. This work implements this method and compares to current methods. This work also plans to extend this method to include blade sweep. While Ishimaru used an analytical turbulence model, others[2-3] calculated the radiated noise using experimentally measured inflow correlations.

Objectives

- Implement the time-dependent wake-rotor lift model proposed by Ishimaru
- Compare its output to current models and data.
- Extend Ishimaru's time-domain model by including blade sweep.

Methodology

Radiated noise can be tied to the unsteady lift on a rotor blade. The lift correlation is the time-domain description of the lift spectrum and can handle the stochastic nature of turbulence. Below is the expression for upwash given by Ishimaru. He assumes the in-wake and out-of-wake turbulence are uncorrelated with each other and defines regions with wake turbulence using the rectangle function.

$$u_{mn}(\tau) = \underbrace{\left\{1 - \sum_{p=-\infty}^{\infty}\sum_{q=0}^{S-1} \mathrm{Rect}\left(\frac{\tau - \frac{2\pi p}{\Omega} - \frac{2\pi q}{\Omega S} + \frac{2\pi m}{\Omega B} - t_{pqm}}{w_{pqm}}\right)\right\}}_{\text{Off while blade is in wake, On out-of-wake}} \underbrace{u^{i}_{mn}(\tau)}_{\text{Inflow turbulent velocity}}$$

$$+ \underbrace{\sum_{p=-\infty}^{\infty}\sum_{q=0}^{S-1} \mathrm{Rect}\left(\frac{\tau - \frac{2\pi p}{\Omega} - \frac{2\pi q}{\Omega S} + \frac{2\pi m}{\Omega B} - t_{pqm}}{w_{pqm}}\right)}_{\text{On when blade is in wake, Off out-of-wake}} \underbrace{u^{q}_{mn}(\tau)}_{\text{Wake turbulent velocity}}$$

$$+ \underbrace{M_{mn}(\tau)}_{\text{Always on; Mean circulation and velocity deficit}}, \qquad (4.28)$$

The lift correlation

$$\mathcal{R}^{\ell\ell}_{mnk\ell}(\tau,\alpha) = \iint_{-\infty}^{\infty} h^{*}_{mn}(\eta_1) h_{k\ell}(\eta_2) \mathcal{R}^{uu}_{mnk\ell}(\tau, \alpha-\eta_2+\eta_1)\, d\eta_1 d\eta_2 \Delta R_n \Delta R_\ell \,. \qquad (3.18)$$

is a convolution of the impulse response with the upwash correlation (equation 4.36, omitted here for brevity).

Some modifications I found necessary to this method are:

- using a modified impulse response that is more appropriate for digital signals
- Using a turbulence model that has a -5/3 power roll off with frequency

Results / Analysis

Calculating the unsteady lift for a single blade section using the time-domain method for a uniform turbulent inflow matches the power spectrum predicted by current models developed in the frequency domain. The usable bandwidth for the time-domain method (in orange) is dependent on the total time simulated and the sampling rate of the simulation. Higher bandwidths can be achieved by modifying those parameters.

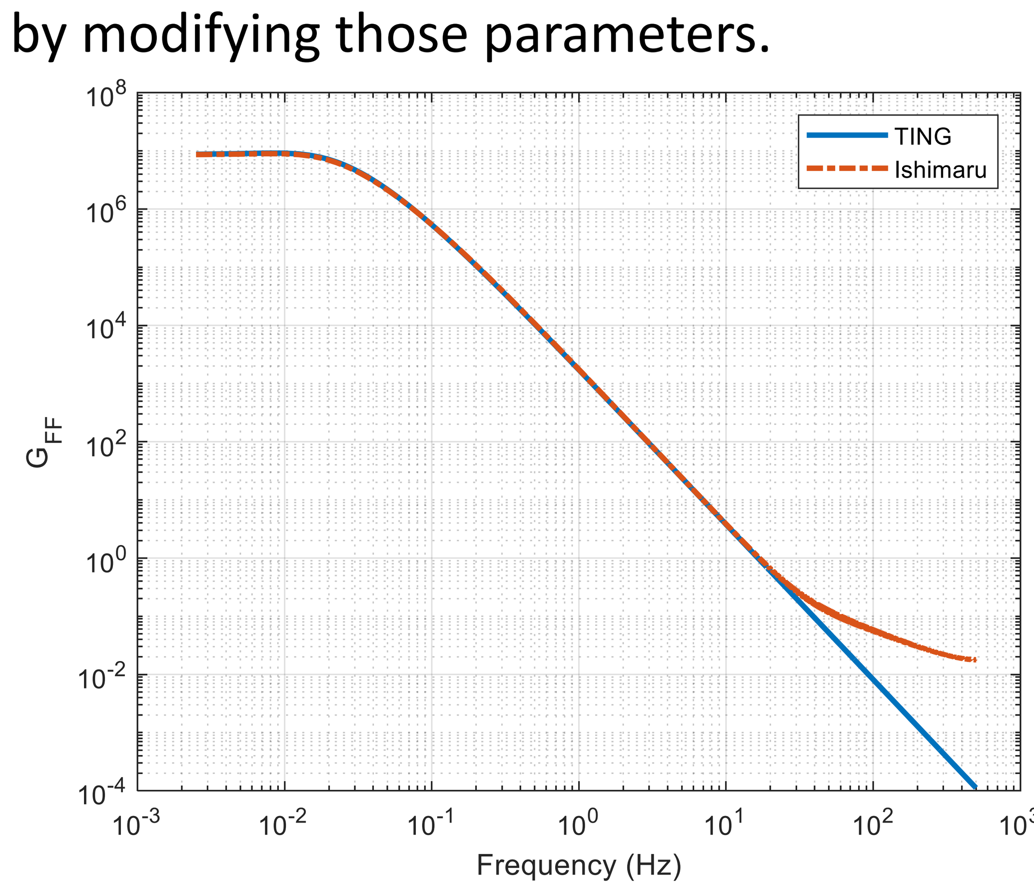

Figure 2: A plot showing the force spectrum calculated for a single blade section subject to a uniform turbulent inflow using a validated frequency domain method (Blue) and the time-domain method (Orange).

The next step is to include multiple blade sections and compare again to current frequency-domain methods.

Future Objectives

Once the time-domain method as Ishimaru derived has been fully implemented, the model will be extended to include blade sweep and blade thickness.

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References

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2. Stewart A.L. Glegg, William Devenport, and Nathan Alexander. Broadband rotor noise predictions using a time domain approach. Journal of Sound and Vibration, 335:115–124, 2015.
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